

A Reanalysis of the MSU Channel 2 Tropospheric Temperature Record

Carl A. Mears, Matthias C. Schabel, and Frank J. Wentz

Remote Sensing Systems

*Manuscript Submitted to Journal of Climate September 27, 2002
Second Revised Version Submitted May 9, 2003*

Corresponding Author

*Carl A. Mears
438 First St. Suite 200
Santa Rosa, CA 95401
mears@remss.com
(707) 545-2904 ext 21*

Note to technical editor: All 14 figures are available in electronic form.

ABSTRACT

Over the period from 1979-2001, tropospheric trends derived from a widely cited analysis of the Microwave Sounding Unit (MSU) temperature record show little or no warming while surface temperature trends based on *in situ* observations show a pronounced warming of ~ 0.2 K/decade. This discrepancy between trends at the surface and in the upper atmosphere has been a source of significant debate. Model predictions of amplification of warming with height in the troposphere are clearly inconsistent with the available observations, leading some researchers to question the adequacy of their representation of the water vapor greenhouse feedback. A reanalysis of the MSU channel 2 data set, with the objective of providing a second independent source of these data, is described in this paper. Our results show a global trend of 0.097 ± 0.020 K/decade, generally agreeing with the work of Prabhakara *et al*, but in disagreement with the MSU analysis of Christy and Spencer, which shows significantly (~ 0.09 K/decade) less warming. We discuss the differences in the various methodologies, and demonstrate that the principal source of these discrepancies is in the treatment of errors due to variation in the temperature of the MSU hot calibration target.

1. Introduction

Researchers generally agree that the surface warming observed over the past century is at least partially anthropogenic in origin, particularly that seen in the past two decades (Hansen et al. 2001, Houghton et al. 2001). In the upper atmosphere the situation is significantly less clear due to the relative paucity and short time period of observations (Hurrell et al. 2000). Radiosondes, the principal tool for atmospheric profiling, have limited spatial coverage, particularly over large portions of the oceans, and are subject to a host of complications including changing instrument types, configurations, and observation practices (Gaffen et al. 2000; Lanzante et al. 2003a; Lanzante et al. 2003b), making long-term climatological studies difficult. While the advent of temperature sounding microwave radiometers flown on NOAA polar orbiting weather satellites provided a new and complementary source of upper atmosphere observations beginning with TIROS-N in 1978 and continuing through the present, the Microwave Sounding Unit (MSU), and the follow-on instrument, the Advanced Microwave Sounding Unit (AMSU), were designed primarily for meteorological rather than climatological purposes. Despite excellent coverage (more than half the earth's surface daily), the MSU data suffer from a number of calibration issues and time-varying biases that must be addressed if they are to be used for climate change studies.

The MSU instruments have four channels spanning the frequency range from 50.2992 to 57.9499 GHz. Thermal emission from atmospheric oxygen constitutes the major component of the measured brightness temperature, with the vertical weighting profile varying from near the surface in channel 1 to the stratosphere in channel 4. In

this work, we focus on MSU channel 2 at 53.74 GHz. About 80% of the signal for this channel comes from the troposphere, with the weighting function peaking from 4 to 7 km above the surface, depending on earth incidence angle. The remainder of the signal comes from the surface and stratosphere, with the exact contribution of each dependent on the surface type and the atmospheric profile at the point of measurement. While other workers have attempted to increase the sensitivity of the MSU 2 measurements to the lower troposphere by employing a differencing scheme to extrapolate the measurements downward to produce the so-called MSU 2LT data, (Spencer and Christy, 1992, 2003, and references therein) this approach amplifies noise and introduces other complications. For this reason, we have chosen to focus on the raw channel 2 data.

Initial studies of the mid-troposphere MSU channel 2 data performed by Christy and Spencer(Christy and Spencer 1995; Christy et al. 1998; Christy et al. 2000; Christy et al. 2003; Spencer and Christy 1990; Spencer and Christy 1992a; Spencer and Christy 1992b), uncovered a number of important sources of error in those data, including intersatellite offsets, the significance of diurnal warming with slow evolution in the satellite local equator crossing times (LECT), and the presence of a significant correlation between observed intersatellite brightness temperature differences and satellite hot calibration load temperature. Impacts of these various contributions were gradually identified and corrected in successive versions of their merged data set, with resulting long-term trends cooling relative to the surface, particularly in the tropics and subtropics. These results, combined with the even more rapid cooling in MSU 2LT, sparked an intense debate centered on their

inconsistency with general circulation model predictions and many surface data sets(Hansen et al. 1995; Santer et al. 1999; Santer et al. 2000; Wallace et al. 1999).

Drawing on work by Trenberth and Hurrell (1997), an investigation of systematic correlations in the MSU2/MSU2LT time series by Wentz and Schabel (1998) revealed the presence of a spurious cooling trend introduced to the MSU2LT data by neglect of the differential effects of satellite orbit decay on the near-limb and near-nadir observations. Accounting for this led to an increase in the global trend of approximately 0.12 K/decade, bringing the lower troposphere observations more in line with model predictions and surface measurements. Christy and Spencer subsequently argued for the presence of additional diurnal and target temperature contributions that largely offset the orbit decay effect, again leading to a surface/troposphere disconnect (Christy et al. 2000). Prabhakara *et al* (1998,2000) also performed an independent analysis of the MSU data set, but their analysis uses a simplified model for the effects of the calibration target temperature than is used either in Christy *et al* (2000, 2003) or the present analysis, thus it is difficult to assess the validity of their approach.

The significance of the MSU data set in climate change research, and the possibility of systematic errors in it, inspired the complete reanalysis described herein. We have developed a completely independent data set based solely on the raw MSU channel 2 observations. This analysis is complementary to that of Christy and Spencer and provides the opportunity to compare and contrast the effects of various corrections on the overall time series and to elucidate the origins of discrepancies between the two.

Data presented in this paper were derived from a comprehensive reanalysis of the raw Level 0 count data for all nine MSU instruments beginning with TIROS-N and ending with NOAA-14. Doing this ensures that there are no common dependencies between our analysis and that of Christy and Spencer, and serves as a useful double-check of our methodology in its entirety. In Section 2 we briefly describe the preliminary calibration steps and quality control procedures involved in producing individual brightness temperature series for each instrument. Section 3 addresses techniques for characterization and removal of incidence angle variations and the diurnal variation of temperature. The involved and critical question of how to intercalibrate observations from different instruments in a consistent way is treated in Section 4, including a discussion of error estimates and correlations. We present results for long-term global and spatially-resolved trends in Section 5, comparing them with the corresponding quantities from the C&S analysis. Section 6 details the principal aspects of the methodologies which we believe account for most of the observed discrepancies between our data and the Christy and Spencer data.

2. Preliminary Quality Control

Preprocessing of the Level 0 (raw counts) MSU data involves a number of quality control and calibration steps, which are briefly described here. Much of the necessary information on data format and calibration is found in the NOAA Polar Orbiter Description (POD) document (Kidwell 1998). Here we focus on two primary elements of the quality control procedure: first, validation of the supplied geolocation

data, and second, production of calibrated brightness temperatures from the supplied raw counts.

Our geolocation quality control procedure utilizes orbital two-line elements (TLEs) provided by the NASA Orbital Information Group (OIG) in conjunction with a satellite orbital propagation model and a geometrical model of the MSU instrument itself to generate predicted geolocation data (Hoots and Roehrich 1980). We use these predicted values to perform basic check on the geolocation values provided by NESDIS, rejecting any footprints for which the distance between predicted and provided earth location exceeds the width of a footprint or for which the nadir angle deviates from nominal by more than 1 degree. At the same time, due to highly unreliable satellite orbital altitude data prior to 1994, we use the orbit propagator to generate exact orbit heights, enabling precise compensation in the final data set for instantaneous altitude variations as well as long-term secular orbit decay effects (Wentz and Schabel 1998).

Basic brightness temperature conversion and calibration is performed by converting raw counts to corrected counts using coefficients that account for radiometer non-linearities determined using pre-launch calibration measurements. Then the earth scene counts are converted to a temperature using the hot-load and cold-space counts, and the measured hot load temperature, using a linear 2-point calibration method. Our final analysis relies on the nominal, NOAA-supplied, calibration coefficients, except for NOAA-12, which utilizes the reconstructed data from (Mo, 1995). We performed additional checks using both simple linear calibration (no non-linearity correction) and the more recent (Mo, et al. 2001)

calibration coefficients and found essentially no difference in the final intercalibrated brightness temperature data. This is presumably due to our incorporation of radiometric nonlinearities in the empirical target factor term discussed in detail in Section 4. Histograms of observed brightness temperatures were accumulated for each satellite and visually inspected to determine appropriate quality control cutoff values. Excepting occasional periods of bad data, the quality control procedure eliminates approximately 0.1% of the observations.

3. Preprocessing of Brightness Temperature Data

Once the individual observations have been processed, but before the MSU Channel 2 brightness temperatures can be merged into a single time series, two important adjustments must be made to remove biases and long-term drifts in the record from each individual instrument.

a. Incidence angle correction.

The MSU instruments are cross-track scanners that measure the upwelling microwave radiance for 11 views with corresponding incidence angles ranging from 0 to 56 degrees. To remove long term effects due to slow, time-dependent decay in the spacecraft's altitude, and to reduce "sampling noise" that occurs when averaging different numbers of measurements from different fields of view (FOV) together, we correct each measurement to an equivalent nadir view, compensating for the slight differences in vertical weighting profile between incidence angles. Correction to nadir is accomplished by computing simulated brightness temperatures both at the observed earth incidence angle (EIA) and at nadir, and then adding the difference of

these to the measured T_b . Simulated brightness temperatures were calculated using interpolated mean monthly NCEP surface and atmospheric profiles from 1996 on a 2.5-degree rectangular grid as input to a well-calibrated radiative transfer model (Wentz and Meissner 1999). Ocean emissivity was determined using a detailed ocean surface model that includes the effects of wind-induced surface roughness and the variation of emissivity with sea surface temperature, while land emissivity was assumed to be fixed. While the constant land emissivity assumption is not necessarily a good one, particularly in regions having snow and ice cover or significant variations in land cover or soil moisture, the low sensitivity of the MSU channel 2 observations to the surface (1-10%, depending on EIA and topographic elevation) and the fact that we are applying a derivative correction makes this a small second order effect.

In addition to secular variation in incidence angle due to satellite orbit decay and small periodic fluctuations in EIA over the course of an orbit, we also noted large, consistent biases between fields of view on opposite sides of the swath in the observations from some instruments. These biases vary in both sign and magnitude between platforms and are generally largest in the early members of the series, and could stem from a number of sources including misalignment of the entire instrument or the beam-directing mirror, or asymmetric distortions of the beam pattern. While their exact origin is difficult to establish, they can be well modeled as an instrumental attitude roll. The effective roll angle needed to remove the cross-swath bias is calculated using a least-squares fit to global observations averaged over three-month periods, with the resulting roll angle used to adjust both land and ocean measurements. The results of the roll regressions are presented in Fig. 1. While there

are small seasonal variations in the roll series for all satellites, noticeable trends are only apparent in NOAA-06 at the end of its operational lifetime, and, to a lesser degree, in NOAA-14. The low frequency time dependence of the roll error is separated from the small seasonal-scale fluctuations arising from model errors in the simulated seasonal cycle by using a third-order polynomial regression to the time series of derived roll errors. Once the time dependence of the roll has been determined, it is removed from each MSU footprint individually based on the simulated NCEP value, interpolated to spatially and temporally coincide with the actual observation. In Fig. 2, we show the results of the incidence angle correction for the January averaged NOAA-6 data. Both the cross scan asymmetry and the difference between the outer and inner scans have been dramatically reduced. Similar plots for the other satellites reveal comparable improvement. Since we use combinations of MSU views that are symmetric around the nadir view, the any error in these adjustments does not cause significant changes in our long-term time series.

b. Diurnal correction.

All of the MSU instruments exhibit the slow drift in local equator crossing time shown in Fig. 3. The principal effect of this drift is to introduce a slow variation in the local time observed by the instrument. This drift in sampling time will cause aliasing of any diurnal signal present into the long term time series, potentially introducing a spurious trend in the measured T_b 's. It is important to note that, while the observations from only ascending or from only descending passes will be dramatically affected by such large changes in LECT, their average will tend to cancel out. In particular, if we decompose the diurnal temperature signal into a

Fourier series, the terms arising from the odd harmonics cancel completely at the equator, due to the 12-hour time difference between observations, and approximately elsewhere. This insensitivity to the dominant first harmonic term is fortuitous in the sense that it minimizes the absolute magnitude of the diurnal effect, but at the same time places stringent requirements on the accuracy of estimation of the shape of the diurnal cycle prior to removing it from the data.

In order to sidestep some of the difficulties encountered in attempting to characterize the diurnal cycle entirely based on the observed data, we developed a method (Mears et al. 2002) based on hourly output from a 5-year run of the NCAR community climate model (CCM3) (Kiehl et al. 1996) to calculate a climatology of local diurnal anomalies in the brightness temperature for each of the 6 distinct view angles measured by the MSU instrument. Recording the model results on an hourly time scale enables us to resolve the shape of the diurnal cycle through the fourth harmonic, the importance of which is discussed above.

Gridded climatologies of hourly/monthly simulated MSU channel 2 brightness temperatures for each of the six distinct MSU FOVs were generated using the CCM3 atmospheric profiles and surface variables in conjunction with our microwave radiative transfer and surface emissivity models (Wentz and Meissner 1999). Over the oceans, we use the comprehensive surface model mentioned above, while over land, we assume a constant emissivity of 0.95, a typical value for dry, vegetated regions.

In Fig. 4 we show characteristic diurnal cycles for the month of June in two locations representing extremes in observed diurnal behavior. Plots (a) and (c) show the diurnal cycle over a grid point in the Western Tropical Pacific for the nadir and

near-limb views, respectively. These two cases reveal small amplitudes and similar shapes dominated by the first harmonic, suggesting a diurnal cycle which arises from heating throughout the troposphere. We find that these features are characteristic of the diurnal behavior over virtually all ocean surfaces, a result consistent with recent microwave sea surface temperature (SST) measurements by (Gentemann et al. 2003) showing that the diurnal cycle amplitude in ocean skin layer temperature is typically less than 0.5K. The net effect of such small, largely sinusoidal diurnal cycles on the long-term time series of combined ascending and descending node measurements is minimal.

Plots (b) and (d) are for a land location in the western United States. Large summer surface warming in this desert location combines with the relatively dry atmosphere and high elevation to produce a large diurnal signal in the simulated brightness temperatures. There is significant reduction in amplitude of the near-limb view relative to the nadir view, indicating that a significant portion of the observed diurnal cycle is due to surface warming, which is attenuated by the longer path through the atmosphere in the near-limb view, rather than heating of the upper atmosphere itself.

Figure 5 shows maps of the diurnal amplitude and the local time of diurnal maximum for the month of June at nadir. We observe that the simulated diurnal cycle has the largest amplitude in high altitude regions, where the surface is less obscured by atmospheric absorption, and in dry regions, which have large near-surface diurnal cycles arising from the interplay between direct solar heating in the day and radiative cooling at night. In contrast, the diurnal amplitude is much smaller in low-altitude,

heavily vegetated land regions and over the ocean where the higher heat capacity tends to dampen day-night variation. In the regions with the largest amplitudes, the brightness temperature peaks shortly after local noon, while land regions with smaller amplitudes show a delayed peak a few hours later. Low- and mid-latitude ocean regions tend to peak even later in the day, though the significance of this is unclear given the vastly reduced amplitude of the signal.

Prior to correction of the long-term time series of MSU brightness temperatures for diurnal drift, we validate our diurnal model by comparing co-located observations of ascending-descending brightness temperature differences (separated by ~ 12 hours near the equator, ~ 10 hours at 65 N or 65 S) with the corresponding simulated differences from the model data. Differences are computed by binning the incidence angle corrected brightness temperatures, averaged over the central five fields of view, by hour of local equator crossing time, with similar histograms formed from the simulation data.

Figure 6 compares the measured and simulated ascending-descending differences for the 15:30 bin for the month of June. The good quantitative agreement between the patterns and amplitudes gives us confidence that the CCM3 model represents the diurnal cycle with sufficient accuracy to be of use in developing a correction. Comparison of the ascending-descending differences for other crossing time bins and months show similar agreement. Correlation coefficients between the measured and simulated maps (spatially smoothed with a boxcar smooth of width 22.5 degrees to reduce sampling noise) are generally above 0.8. The most apparent model inaccuracies are a slight overestimation of the diurnal cycle over tropical

forests (visible in tropical Africa and the Amazon Basin) and a slight underestimation of the diurnal cycle in some high latitude land areas (visible in northwestern Canada and eastern Siberia), possibly due to our assumption of constant land surface emissivity. Except in the dense rain forest, our value of 0.95 is probably an overestimate; also, seasonally varying snow cover and soil moisture have a large time-varying effect on emissivity and on the vertical weighting function (Shah and Rind 1995). Future refinement of this data set will include an improved land surface emissivity model.

Using the diurnal climatology simulated from CCM3, we adjust all MSU measurements to the same local time so that drifts in the measurement time no longer affect any deduced long-term trends. In Fig. 7 we plot the global correction applied to the time series for each satellite with the corrected local reference time chosen to be 12:00 noon for all observations. The choice of reference time has essentially no effect on the long-term trend series, since choosing a different time simply adds the same periodic signal with a constant offset to all satellites. An additional validation step based on residuals of intersatellite differences will be discussed in detail in Section 4.

4. Intersatellite Merging Methodology

The final, and most crucial, step in constructing a composite time series of the MSU temperatures is that of merging the data from the nine instruments into a single time series of measured temperatures. Differences in the calibration offsets and nonlinear responses of the specific instruments, as well as residual errors stemming

from incomplete correction of diurnal biases, lead to corresponding offsets in the measured brightness temperatures which must be removed before constructing a combined time series. A important factor, as noted in a previously, is the presence of strong correlations between the measured brightness temperature and the temperature of the hot calibration target(Christy et al. 2000, 2003; Prabhakara et al. 2000). The exact cause of this so-called “instrument body effect” (IBE) is not known, but its presence in all of the MSU instruments strongly suggests that it stems from unresolved errors in the measurement and subsequent removal of radiometer non-linearities. An error model for brightness temperature incorporating the IBE, first introduced by Christy et al, (Christy et al. 2000) is

$$T_{MEAS,i} = T_0 + A_i + \alpha_i T_{TARGET,i} + \varepsilon_i, \quad (1)$$

where T_0 is the true brightness temperature, A_i is the temperature offset for the i -th instrument, α_i is a small “target factor” describing the correlation of the measured temperature with the temperature of the hot calibration target, $T_{TARGET,i}$ is the target temperature anomaly for the i -th satellite, and ε_i represents unresolved residual errors. Prabhakara *et al* use a similar method, except that only a single target factor is used for all satellites (Prabhakara et al. 2000). In the following sections we show that different target factors α_i are necessary to accurately match the overlapping observations, confirming the earlier observations of Christy and Spencer (hereafter CS). We also perform a detailed analysis of the uncertainty in the deduced values of the A_i ’s and α_i ’s, focusing on the strong error correlations and their ramifications for error estimates of long-term trends in brightness temperature.

a. Ocean-only merging

Our analysis of inter-satellite merging is restricted to ocean-only observations. As discussed in the previous section, the diurnal cycle over the oceans is much smaller and smoother than over land, and is less likely to cause significant errors in either the retrieved values of the merging parameters or in the resulting merged time series.

Determination of the inter-satellite merging parameters begins with pentad (5-day) averages of global brightness temperature for each field of view to reduce noise. We assume that merging parameters depend solely on the instrument, and are independent of geolocation and orbital node as tests using zonally varying merging parameters revealed little significant difference in the final trend statistics or merging parameters. Global oceanic pentad averages are determined from averages of 5-degree zonal pentad series, area-weighted for each field of view separately over the latitude range from 85S to 85N. If the number of individual data points in any pentad fell below 95% of the median value for that zonal band, that pentad was discarded to guard against systematic non-uniform spatial sampling due to extended periods of missing data. The final global series presented here are averages over the central five fields of view, providing a global near-nadir pentad time series for each instrument.

For each pentad that includes valid averages from more than one satellite, we construct the following difference equation for each distinct pair of satellites for each pentad denoted by time t_n :

$$T_{diff}(t_n) = T_{MEAS,i}(t_n) - T_{MEAS,j}(t_n) = A_i + \alpha_i T_{TARGET,i}(t_n) - A_j - \alpha_j T_{TARGET,j}(t_n) + \varepsilon_i - \varepsilon_j. \quad (2)$$

The absence of an absolute external calibration reference requires us to choose a single baseline brightness temperature as the arbitrary reference offset; here we set $A_{NOAA-10}$ to be 0.0, leaving us with a system of many linear equations (~1200

overlapping pentads) in seventeen unknowns (eight offsets + nine target factors). We solve the resulting system of equations using multiple linear regression, simultaneously minimizing the sum of squared differences between satellites.

Figure 8 presents the results of this merging calculation. The fit does an excellent job at accounting for not only the large inter-satellite offsets, but also for the significant seasonal-scale fluctuations, which are highly correlated with the target temperature differences. These fluctuations are especially large for satellite pairs that include data from NOAA-11 after 1992, when the target temperature for NOAA-11 began to experience large variations due to its drift to later crossing times. With the regression coefficients from this fit, we are able to generate a complete merged time series of brightness temperatures from all nine instruments simply by averaging together the individual pentad data corrected by application of the regressed offset and target, followed by a median filter to remove outliers.

b. Estimating errors in trends

When computing trends, it is critical to estimate the uncertainty in the resulting estimates, and to ascertain the specific merging parameters that contribute to the most to the final error budget. The covariance matrix derived from our multiple regression analysis contains the needed information both about the errors in each parameter and about correlations between errors in different parameters. We use a Monte-Carlo approach to estimate the uncertainties in the trend along with the sensitivity of the trend to changes in individual parameters. We would like to stress that the error estimates we obtain in this way are only estimates of the internal statistical errors, and

do not include possible errors due to error in the diurnal adjustments, or undetected instrument drift.

The covariance matrix is dependent on our estimate of the measurement errors for the intersatellite differences, estimated by analyzing the distribution of the after-the-fit residuals. We approximate the random errors in the inter-satellite differences by the standard deviation of the residuals for all the satellite pairs combined, presented in Table 1. Since the residuals exhibit a significant lag-1 (pentad) autocorrelation ρ of ~ 0.40 , we adjust the final uncertainties in offsets, target factors, and trends by $\sqrt{(1+\rho)/(1-\rho)} = 1.52$ to account for reduction in degrees of freedom implied by this autocorrelation.

To perform our Monte Carlo analysis, we generated an ensemble of 30000 sets of 17 correlated random deviates with statistical properties consistent with the covariance matrix. These correlated deviates were added to the fitted parameters to obtain an ensemble of 30000 “noisy” sets of merging parameters. We then calculated combined T_b time series corresponding to each noisy set and performed linear regression on the resulting noisy time series to obtain a “noisy” set of trends, the standard deviation of which is used in our estimate of the overall trend error.

While this procedure yields a consistent estimate of the error in the trend, it does not provide any insight into the sensitivity of the trend to the choice of any one particular merging parameter, nor does it establish which pairs of satellites have the most critical overlap regions. In order to understand the individual contributions to the overall error, we performed a regression virtually identical to that described above, but using the intersatellite temperature differences as the prognostic variable,

enabling us to separate out the individual contributions of each overlap pair to the overall trend. The resulting covariance matrix is used to create sets of ‘noisy’ intersatellite differences and target temperature multipliers, as previously described, and the sensitivity of the final trend to each individual parameter determined from linear regression to the simulated trends.

The presence of large off-diagonal terms in the covariance matrix of merging parameters, plotted in Fig. 9, demonstrates the presence of strong correlations between certain pairs of parameters. In particular, it is notable that both the NOAA-09 offset and the NOAA-09 target temperature factor are relatively poorly constrained and strongly interdependent. The intersatellite difference sensitivity analysis presented in Table 2 shows that most of the intersatellite differences are well defined, with standard deviations below 0.005K. Notable exceptions are those parameters involving NOAA-09/NOAA-10, NOAA-08/NOAA-09, and NOAA-07/NOAA-09 overlap, with standard deviations in the range of >0.01K. The overall trend is also quite sensitive to the NOAA-09/NOAA-10 offset. The combination of large error and large sensitivity leads to a correspondingly large contributions to the trend error, with the contribution from the NOAA-09/NOAA-10 overlap contributing more than twice the error as any other overlap. In Table 3, we present results of a similar sensitivity analysis for the target temperature factors. Again, the parameters are all well defined except for that associated with NOAA-09, which contributes to the overall trend an error almost 3 times the contribution of any other target factor.

Based on this sensitivity analysis, the weakest link in the satellite merging analysis appears to be the NOAA-09/NOAA-10 overlap, since it is critically located

in the center of the time series and spans only 19 pentads. The value of the NOAA-09/NOAA-10 difference is also strongly correlated with the NOAA-09 target factor due to the nearly monotonic increase in NOAA-09's target temperature during its lifetime, making this target temperature factor critical for connecting the NOAA-06/NOAA-09 overlap with the later NOAA-09/NOAA-10 overlap.

c. Land-only and global merging

We now address extension of the merging procedure for ocean-only data to the land-only and land-and-ocean brightness temperatures. In merging these data sets, we use the target factors from our ocean-only analysis. We have greater confidence in our ability to determine these factors accurately for two reasons. First, there is significantly greater variability of the globally averaged brightness temperatures over land, due to diurnal effects and uneven sampling of land regions with different brightness temperatures between separate 5-day averaging periods. This leads to increased noise in the global land pentad averages that in turn increases the error in the fitted parameters. Second, the values of the target factors deduced are influenced by the sampling of the diurnal cycle along with the details of our diurnal correction. These corrections are larger, and therefore likely to have larger errors, over land. This is especially important for NOAA-11, where there is a long-term drift in the target temperatures and a long-term diurnal correction of approximately the same shape. By using the oceanic values for the target factors, both problems are avoided. We also expect the target factors to be the same over land as over ocean, since the error in the satellite measurements and the time-dependence of the target temperature should be unaffected by whether the instrument is viewing a land or ocean scene. In

contrast, we do not necessarily expect the satellite offsets to be identical, since the different data subsets sample different parts of the diurnal cycle (which may not be perfectly removed), and there may be unaccounted for residual non-linear instrumental effects, leaving scene-temperature dependence in the average offset. The data confirm our suspicions; offsets must be recalculated for each data subset to avoid small but significant (typically $<0.04\text{K}$) discontinuities in the residuals to the merging fit. Both ocean-only, land-only, and land and ocean offsets for each instrument are shown in Table 4.

In Fig. 10, we show the results of a merge analogous to those shown in Fig. 8, applied to the land-only data. Measurements whose altitude exceeds 1500m at the center of the measurement footprint are excluded from the global land-only merging process to reduce the effects of surface emission. We only plot the NOAA-11/NOAA-12 overlap, since the effects of the diurnal cycle are the most important for this overlap. During the four-year overlap period from 1991-1995, the ascending LECT for NOAA-11 drifted from 15:00, just after the peak of the diurnal cycle, to 19:30, experiencing significant diurnal cooling. In contrast, over the same period the NOAA-12 crossing times were nearly stable, contributing little diurnal temperature drift. The effect of this differential drift in LECT is an apparent cooling of the NOAA-11 global averages relative to NOAA-12, giving rise to a slope in the residuals shown in Fig 10a.

When we repeat the calculation using data corrected for the diurnal cycle with the correction outlined in Section 3, we obtain the results shown in Fig. 10b. From the figure it is apparent that the NOAA-11/NOAA-12 slope during 1991-1995 is

mostly eliminated. Seasonal-scale oscillations in the NOAA-11/NOAA-12 residuals that have been also been reduced (but not eliminated) by the diurnal correction. These seasonal scale fluctuations represent a potential source of uncorrected systematic error, since they could, if present in the critical NOAA-09/NOAA-10 overlap interval, lead to errors in the corresponding brightness temperature offset.

To test the possibility that our diurnal correction is over- or under-compensating, we performed an analysis of the dependence of the global temperature trend on a linearly-scaled version of the initially determined correction term. As shown in Fig. 11, the trend itself shows a linear dependence on the scaled diurnal correction, while the residual RMS goodness-of-fit measure shows a smooth evolution toward a minimum near a scaling factor of 1.0. This provides further support for the argument that our model-based diurnal signal is accurately representing the overall global diurnal contribution to the overall MSU time series.

5. Trends in MSU Mid-Tropospheric Temperatures

Given that much of the interest in the MSU temperature time series centers on long-term climatological trends, we focus on these in the following discussion. Note that the inter-satellite offsets are, in a number of cases, sufficiently large that to neglect them would noticeably impact analysis of seasonal or interannual fluctuations. For this reason, we believe that the reanalyzed data will be of interest not only to researchers in climate change but also to those studying other phenomena such as surface-atmosphere coupling or temperature impacts of volcanic aerosols.

In Figure 12 we plot monthly average (85S-85N) time series of MSU 2 brightness temperature anomaly for three different subsets of the data: a) ocean-only, b) land-only, and c) both land and ocean. The lower portion of each panel has Remote Sensing Systems' (RSS) reanalyzed data plotted in black, with the equivalent series from CS (version 5.0, 2003) shown in gray for comparison. Difference curves for the two analyses are plotted in the upper portion of the panel. While the interannual fluctuations in temperature reveal an extremely high degree of correlation in all three cases, it is apparent from the difference curves that the linear trends for the two data sets differ significantly. The origins of this discrepancy will be discussed in depth in Section 6.

Table 5 presents the values for regressed linear trends for the RSS data set, both with and without the diurnal correction applied, for the CS data set corresponding to each of the three plotted subsets, and the global trend value for the Prabhakara *et al* data set over the time period 1979-1999. Our trend values are provided with $2\text{-}\sigma$ error bounds calculated using the Monte Carlo procedure outlined in Section 3, and with the corresponding RMS value of the fit residuals. Over the ocean, where diurnal drift is unlikely to have a significant influence on the series, we observe a warming trend of 0.099 K/decade, in clear contrast with the slight cooling trend (-0.011 K/decade) derived by CS. As anticipated, our warming trend only decreases by 0.008 K/decade when the diurnal correction is not applied.

Over land we note a significantly increased sensitivity to the diurnal correction, with the uncorrected warming of 0.023 K/decade increased significantly to 0.087 K/decade by its application. The CS value of 0.050 K/decade warming is closer to

our trend than the ocean-only observations, leading to a CS land-ocean differential more than twice that found in the RSS data. Our global trend for both land and ocean combined is 0.097 K/decade, essentially the area-weighted average of the land and ocean data, and shows nearly 0.1 K/decade greater warming than the corresponding CS analysis. The relatively small sensitivity of the land and ocean trend to the application of the diurnal correction indicates that errors in the correction procedure will have a small effect on the deduced global trends.

The spatial distribution of trends for the RSS and CS data, shown in Fig. 13, provides a method of evaluating in more detail the characteristic fingerprint of change in the MSU 2 observations. Monthly anomalies were computed using target factors derived from the ocean-only data and offsets determined from the combined land and ocean data set, providing a set of 2.5 degree maps for the entire MSU channel 2 dataset. Corresponding monthly time series were generated for each grid cell from the anomaly maps, with trends for each series determined by simple linear regression (Fig. 13a). An identical procedure was applied to the CS monthly anomaly data, providing a comparable map of their trends (Fig. 13b). The difference between RSS and CS trends is shown in Fig. 13c. Apparent in the CS trend map is an enhanced longitudinal smoothness, an effect which probably stems from their zonal interpolation methods (Spencer and Christy 1992a), accompanied by a corresponding decrease in meridional smoothness which may be attributable to their use of zonally-dependent merging coefficients.

Both the RSS and CS trend maps show significant warming in the northern hemisphere, and their zonal profiles seem quite similar in shape despite the global

trend offset of 0.1 K/decade. However, examination of the zonal difference map in Fig. 13c reveals a strong latitude-dependence of the offset, with a clear upward step between 30N and the Equator. In the high northern latitudes where large regions of significant warming over Siberia and northeastern Canada are observed, and where the most of the high quality radiosonde observations used in validations of the CS data set reside, the two data sets are in generally good agreement, both in terms of the characteristic spatial patterns and in absolute trend magnitude. Two notable exceptions are over northern Africa, where we observe significant warming relative to CS, and the Himalayas, where we see much less warming than CS, perhaps due to difference in the details of our respective diurnal temperature corrections.

The tropics and southern high latitudes, in contrast, show significant biases between the RSS data and the CS data. Both data sets reveal significant cooling in the southern oceans and over Antarctica, but the magnitude of this is much smaller in our analysis. Elsewhere, with the prominent exception of the equatorial Pacific where the CS data show strong cooling trends in contrast to the very slight warming seen in our data, the results appear to differ by an almost constant offset. These results make it clear that any attempts to validate global MSU temperature trend data with radiosonde or other *in-situ* observations must take great care to sample the globe as uniformly as possible (Hurrell et al. 2000). Such efforts may be stymied by the preponderance of observing stations in the northern hemisphere and the paucity of reliable observations of any sort over the southern oceans.

6. Discrepancies between the RSS and C&S Analyses

There are number of differences in methodology between RSS and CS that may contribute to the observed discrepancy in deduced trends. In Table 6, we summarize differences between the two methods that could significantly change the long-term global time series. First, there are significant differences in the origin and application of the adjustments used to correct for diurnal drift. We calculate the diurnal cycle for each 2.5 x 2.5 degree grid point using a GCM (CCM3), and then validate it in a number of ways using consistency with MSU data. Christy and Spencer account for diurnal drifts by considering systematic cross-scan differences between measurements taken at slightly different local times (Christy et al. 2000, 2003), thus deducing effect of diurnal drift directly from the MSU measurement themselves. Despite this difference, on a *global* scale, the two adjustments are in good agreement with each other. When we reprocess our data using the CS diurnal correction, the global trend is decreased only 0.006 K/decade, less than 7 percent of the total difference between our results.

A more important difference between our methodologies is the way in which we determine the intersatellite merging parameters. We use a unified approach where each overlapping pentad average is used with equal weight to determine both the target factors and intersatellite offsets. The equal weighting of each 5 day overlap serves to de-emphasize periods of short overlap without ignoring them altogether. Christy and Spencer (2000,2003) impose a minimum time period over which an overlap must occur before it can be taken into account to help determine the merging parameters. This leads CS to discard the TIROS-N/NOAA-06, NOAA-07/NOAA-09,

NOAA-08/NOAA-09, NOAA-09/NOAA-10 and NOAA-10/NOAA-12 overlaps when determining their target factors. Their intersatellite offsets are then determined by evaluating the mean difference between co-orbiting satellites utilizing a single path that connects all the satellites in question.

Ultimately these differences in analytical methodology result in significantly different values for the NOAA-09, and to a lesser extent NOAA-11, target factors. When we implement the CS merging procedure and diurnal correction, but use our 5-day land-and-ocean pentad-average data, we obtain a value for the NOAA-9 target factor of 0.075, almost as large as the value of 0.095 reported by CS. As we noted in section 3, the bulk of the trend discrepancy between the RSS and CS analyses of the MSU 2 dataset arises from a short, nearly step-like transition in the time period between 1985 and 1987, corresponding to the interval during which NOAA-09 constituted a critical link between the earlier and later instruments, and a slow ramp from 1991-1995, corresponding to the large drift in LECT for NOAA-11, causing both a large diurnal drift, and large fluctuations in the calibration target temperatures, which amplify the relatively small differences in NOAA-11 target factors and in our diurnal adjustment procedures. Figure 14 shows the target factors for all satellites for two different versions of our methodology, one with and one without any added diurnal corrections, along with corresponding factors from CS (Christy et al. 2003). Except for NOAA-09, almost all of our target factors are also in good agreement with those found by CS, and in rough agreement with the single, satellite independent target factor of 0.03 found by Prabhakara et al (Prabhakara et al. 2000).

The CS target coefficient calculation focuses on reducing low frequency differences during the overlapping periods. The use of the CS coefficient for NOAA-9 reduces the intersatellite trend between NOAA-6 and NOAA-9 seen in Fig. 8 from 0.04K/yr to -0.01 K/yr, but at the expense of significantly increasing other intersatellite difference trends, especially those ignored by Christy and Spencer.

In order to quantify the effect of the differing NOAA-09 target factors, we exactly reproduced our ocean-only merging procedure with the sole exception that we fix the value of the NOAA-9 target factor to the CS value of 0.095, the trend value becomes 0.022 K/decade, a difference of 0.073, indicating that differences in this one target factor are responsible for a large fraction of the overall difference between these analyses. This difference is slightly larger than would be expected (0.060) from our Monte Carlo analysis presented above. In this case, the other target factors are held fixed, while in the Monte-Carlo case, they vary according to their respective correlations with the target factor in question. When CS perform a similar study using their data and RSS target coefficients, they report a difference of only 0.05 K/decade (Christy, 2003, private communication).

Another difference between our analyses is in the amount of temporal smoothing performed before calculating merging parameters. We use pentad averages in our regression procedure, while CS use 60 to 120-day averages when calculating target factors. We reanalyzed our data after performing a 60-day running mean average on the global oceanic pentad averages. This resulted in small changes in our target factors that resulted in a decrease in global trend from 0.098 to 0.096K/decade.

7. Summary

We have performed a complete end-to-end reanalysis of the MSU channel 2 tropospheric temperature data, including extensive geolocation and data quality control measures, corrections for incidence angle variation, orbit decay, and satellite roll error, a new diurnal correction methodology based on GCM simulations of the diurnal cycle, and a multiple linear regression merging algorithm which incorporates all available overlapping observations in a uniform and self-consistent error model. Monthly maps of mean brightness temperature from our analysis are available via the world wide web at http://www.remss.com/msu/msu_browse.html.

As a diagnostic criterion, we compare long-term decadal trends derived from our data set with trends in the Christy and Spencer data set over an identical interval, revealing a difference of approximately 0.09 K/decade, with our analysis warming significantly more than theirs. On shorter time scales, the two sets of observations are virtually indistinguishable. While all of the corrections are important, the primary source of disagreement is in the nonlinear target factor for the NOAA-09 instrument. This platform ties together the preceding and successive instruments through an extremely short 17-pentad overlap period with NOAA-10, making the final series quite sensitive to its merging parameters. For this particular instrument the fractional contribution of the correction for non-linearity made by the target multiplier in the Christy and Spencer analysis is ~10%, more than five times our corresponding multiplier and more than three times larger than the multiplier for any other instrument. By itself, this difference is responsible for ~0.07 K/decade of the overall difference in the decadal trends, with the remainder arising from our differing

treatments of the diurnal temperature cycle and differences in the NOAA-11 target factor.

A number of studies of tropospheric temperatures as measured by radiosondes have found 0.1 to 0.2 K/decade less warming than we see in our results (Angell 2000; Lanzante et al. 2003b; Parker et al. 1997). Recent studies have found that the trends determined for individual radiosonde observation stations can vary by more than 0.1 K/decade depending on adjustments made for temporal inhomogeneities in instrumentation or observing practice(Gaffen et al. 2000; Lanzante et al. 2003b), and differences in derived trends between different versions of the same global data sets can change by almost this amount(Santer et al. 1999). Based on these results we think it is not appropriate to use radiosonde comparisons as the single method for validating satellite derived temperature trends, and studies, such as ours, that are primarily based on internal consistency should be considered on equal footing.

8. Acknowledgement

This work was performed under the auspices of the NOAA Climate and Global Change Program and the Joint NOAA/NASA Enhanced Data Set Project.

References

- Angell, J. K. (2000). "Tropospheric temperature variations adjusted for El Niño, 1958-1998." *Journal of Geophysical Research* **105**: 11841-11849.
- Christy, J. R. and R. W. Spencer (1995). "Assessment of precision in temperatures from the microwave sounding units." *Climatic Change* **30**: 97-102.
- Christy, J. R., R. W. Spencer and E. S. Lobl (1998). "Analysis of the merging procedure for the MSU daily temperature time series." *Journal of Climate* **11**: 2016-2041.
- Christy, J. R., R. W. Spencer and W. D. Braswell (2000). "MSU Tropospheric Temperatures: Dataset Construction and Radiosonde Comparisons." *Journal of Atmospheric and Oceanic Technology* **17**(9): 1153-1170.
- Christy, J. R., R. W. Spencer, W. B. Norris, W. D. Braswell and D. E. Parker (2003). "Error Estimates of Version 5.0 of MSU/AMSU Bulk Atmospheric Temperatures." *Journal of Atmospheric and Oceanic Technology* **In Press**.
- Gaffen, D., M. Sargent, R. Habermann and J. Lanzante (2000). "Sensitivity of tropospheric and stratospheric temperature trends to radiosonde data quality." *Journal of Climate* **13**: 1776-1796.
- Gentemann, C. L., C. J. Donlon, A. Stuart-Menteth and F. J. Wentz (2003). "Diurnal signals in satellite sea surface temperature measurements." *Geophysical Research Letters* **30**(3): 1140.

- Hansen, J., H. Wilson, M. Sato, R. Ruedy, K. Shah and E. Hansen (1995).
“Satellite and surface temperature data at odds?” *Climatic Change* **30**:
103-117.
- Hoots, F. R. and R. L. Roehrich (1980). Spacetrack Report No. 3:
www.celstrak.com/NORAD/documentations/spacetrk.pdf.
- Kidwell, K. B. (1998). NOAA Polar Orbiter Data Users Guide, National Climatic
Data Center.
- Kiehl, J. T., J. J. Hack, G. B. Bonan, B. A. Boville, B. P. Briegleb, D. L.
Williamson and P. J. Rasch (1996). Description of the NCAR Community
Climate Model (CCM3). Boulder: National Center for Atmospheric
Research.
- Lanzante, J., S. Klein and D. Seidel (2003a). “Temporal Homogenization of
Monthly Radiosonde Temperature Data. Part I: Methodology.” *Journal of
Climate* **16**: 224-240.
- Lanzante, J., S. Klein and D. Seidel (2003b). “Temporal Homogenization of
Monthly Radiosonde Temperature Data. Part II: Trends, Sensitivities, and
MSU comparison.” *Journal of Climate* **16**: 241-262.
- Mears, C. A., M. Schabel, F. J. Wentz, B. D. Santer and B. Govindasamy (2002).
“Correcting the MSU middle tropospheric temperature for diurnal drifts.”
*Proceedings of the International Geophysics and Remote Sensing
Symposium III*: 1839-1841.

- Mo, T. (1995). "A Study of the Microwave Sounding Unit on the NOAA-12 Satellite." *IEEE Transactions on Geoscience and Remote Sensing* **33**: 1141-1152.
- Mo, T., M. D. Goldberg and D. S. Crosby (2001). "Recalibration of the NOAA microwave sounding unit." *Journal of Geophysical Research* **106**(D10): 10145-10150.
- Parker, D. E., M. Gordon, D. P. N. Cullum, D. M. H. Sexton, C. K. Folland and N. Rayner (1997). "A new global gridded radiosonde temperature data base and recent temperature trends." *Geophysical Research Letters* **24**: 1499-1502.
- Prabhakara, C., J. R. Isaacovazzi, J.-M. Yoo and G. Dalu (2000). "Global warming: Evidence from satellite observations." *Geophysical Research Letters* **27**(21): 3517-3520.
- Santer, B. D., J. J. Hnilo, T. M. L. Wigley, J. S. Boyle, C. Doutriaux, M. Fiorino, D. E. Parker and K. E. Taylor (1999). "Uncertainties in 'observational' estimates of temperature change in the free atmosphere." *Journal of Geophysical Research* **104**: 6305-6334.
- Santer, B. D., T. M. L. Wigley, D. J. Gaffen, L. Bengtsson, C. Doutriaux, J. S. Boyle, M. Esch, J. J. Hnilo, P. D. Jones, G. A. Meehl, E. Roeckner, K. E. Taylor and M. F. Wehner (2000). "Interpreting differential temperature trends at the surface and in the lower troposphere." *Science* **287**: 1227-1232.

- Shah, K. P. and D. Rind (1995). "Use of microwave brightness temperatures with a general circulation model." *Journal of Geophysical Research* **100**(D7): 13841-13874.
- Spencer, R. W. and J. R. Christy (1990). "Precise Monitoring of Global Temperature Trends from Satellites." *Science* **247**: 1558-1562.
- Spencer, R. W. and J. R. Christy (1992a). "Precision and Radiosonde Validation of Satellite Gridpoint Temperature Anomalies. Part I: MSU Channel 2." *Journal of Climate* **5**: 847-857.
- Spencer, R. W. and J. R. Christy (1992b). "Precision and Radiosonde Validation of Satellite Gridpoint Temperature Anomalies. Part II: A Tropospheric Retrieval and Trends during 1979-1990." *Journal of Climate* **5**: 858-866.
- Trenberth, K. E. and J. W. Hurrell (1997). "Response to "How accurate are satellite 'thermometers'?"." *Nature* **389**: 342-343.
- Wallace, J. M., J. R. Christy, D. J. Gaffen, N. C. Grody, J. E. Hansen, D. E. Parker, T. C. Peterson, B. D. Santer, R. W. Spencer, K. E. Trenbreth and F. J. Wentz (1999). Reconciling Observations of Global Temperature Change. Washington D.C., National Research Council.
- Wentz, F. and T. Meissner (1999). AMSR Ocean Algorithm (Version 2). Santa Rosa, Remote Sensing Systems.
- Wentz, F. J. and M. Schabel (1998). "Effects of satellite orbital decay on MSU lower tropospheric temperature trends." *Nature* **394**: 661-664.

Figure Captions

Figure 1. Time series of retrieval, for each satellite for MSU channel 2. The colored symbols are the retrieved rolls, and the black crosses are the results of a polynomial fit to the time dependence of the roll error. Other than the anomalous time dependence of the NOAA-06 bias and a slight trend in NOAA-14, the roll errors are nearly constant in time.

Figure 2. Example of incidence angle adjustment. In (a), we plot the zonal averaged differences between all measurements in a given field of view and the central field of view. Each line corresponds to the average over a 5-degree zonal band, starting at 75 S and finishing at 75 N. This plot is made by averaging all NOAA-06 measurements made during the month of January. Note the asymmetry between the right and left sides of the scan. To highlight this asymmetry, in (c) we plot the difference between a given field of view, and its corresponding field of view on the opposite side of the scan. In (b) and (d), we plot corresponding plots for the same data after we apply our incidence angle adjustment, referring each measurement to the nadir view, and taking into account the retrieved effective roll from Figure 1.

Figure 3. Ascending node local equator crossing time (LECT) for each MSU instrument.

Figure 4. Simulated MSU Channel 2 diurnal cycles calculated from hourly CCM3 output for the month of June. (a) and (c) are for a 2.5 x 2.5-degree box in the tropical Pacific, centered at 178.75 W, 1.25 N. (b) and (d) are for a 2.5 x 2.5 degree box in the western United States, centered at 113.75 W, 38.75 N.

Figure 5. (a) Mean simulated MSU Channel 2 diurnal peak-to-peak amplitude for June at the nadir view. (b) Mean local time of simulated diurnal maximum, with the amplitude of the diurnal cycle denoted by the saturation of the color (this is done so the reader is not confused by anomalous diurnal maxima caused by noise in regions with small diurnal amplitude).

Figure 6. (a) Ascending-descending channel 2 brightness temperature differences for the entire MSU dataset for the central 5 fields of view, the month of June, and for ascending node equatorial crossing times between 15:00 and 16:00. The roughly periodic variation visible in the southern oceans is due to non-uniform sampling of the seasonal cycle. (b) Same as (a), except simulated using the CCM3 diurnal climatology.

Figure 7. Effect of the diurnal correction on global pentads. Each line is a plot of the difference between global 5-day averages with and without the diurnal correction applied. Symbols are plotted at periodic intervals to help the reader identify which line represents each satellite in regions where they overlap.

Figure 8. Results of the satellite merging calculation, plotted separately for each satellite pair. In each plot, gray dots represent oceanic pentad averages of brightness temperature differences between pairs of satellites, and the black dots are a fit to the differences, using only both constant satellite offsets and target factors. The black crosses are the residuals to the fit, offset for clarity. The line through the black crosses is a horizontal line at zero residual to guide the eye.

Figure 9. Lego plot of the covariance matrix for ocean-only data. The first 12 parameters starting from the upper left corner of the surface, correspond to the intersatellite differences, shown in the same order as in Table 6.2. The last 9 correspond to the target multipliers. The on-diagonal elements are the variance of each parameter, so large values show those parameters that are poorly determined. Large positive or negative off-diagonal terms indicate strong correlations between the parameters. The differences involving NOAA-09, and the NOAA-09 target temperature are both poorly constrained and strongly correlated.

Figure 10. Results of the satellite merging calculation analogous for the NOAA-11/NOAA-12 overlap period. The gray dots are the NOAA-11/NOAA-12 differences. The black dots represent the fit to the differences using the ocean-only target multipliers. The black crosses are the after the fit residuals, offset so that the horizontal line is zero. (a) Merge performed without the diurnal correction. Note the overall slope of the residuals in the 1992-1995 time period due to the drift in local crossing time of NOAA-11. (b) Merge

performed using the diurnal correction. Note the marked reduction in the slope and the seasonal cycle in the residuals. This provides another check on the validity of the CCM3-based diurnal correction.

Figure 11. The dependence of the RMS fit residuals on multiplicative scaling of the diurnal correction derived from the CCM3 model (squares, scale on left), and the derived decadal trend plotted for each scaling factor (circles, scale on right).

Figure 12. Trends in global MSU channel 2 brightness temperatures. (a) Ocean-only global time series. In the pair of traces, the black trace is the monthly time series we found, while the gray corresponds to the ocean-only time series from Christy and Spencer, Version 5.0. The black line is a linear fit to our time series, and the gray line is a fit to the Christy and Spencer time series. The top trace shows a difference time series ($T2_{RSS} - T2_{CS}$), offset by 1.5K. Note that most of the difference between these two data sets occurs during the 1985-1987 time period when NOAA-09 was active. (b) Same as (a), except for land only observations. (c) same as (a), except for land and ocean data combined.

Figure 13. Color-coded map of global MSU channel 2 brightness temperature trends for the period 1979-2001 for the RSS (a) and CS Version 5.0 (b) data sets. The spatial distribution of trend differences (RSS-CS) is plotted on the same scale in (c).

Figure 14. Comparison of target temperature factors. The two sets of RSS derived target temperature factors were calculated using ocean-only data. The Christy and Spencer target temperature factors were obtained using both land and ocean data, Version 5.0. Note the general agreement between the RSS values and the C&S values, except for NOAA-09.

Table 1. Estimated Errors in Intersatellite Pentad Differences

Data subset	Standard deviation of residuals to fit
Ocean Only	0.033 K
Land Only	0.064 K
Ocean and Land	0.031 K

Table 2. Inter-satellite Sensitivity Analysis

Satellite 1	Satellite 2	# of overlapping pentads	Intersatellite Difference (K)	Std. Dev. of Intersatellite Difference (K)	Sensitivity of Trend (dTrend/dDiff) (Decade ⁻¹)	Estimated Contribution to Std. Dev. of Trend(K/Decade)
TIROS-N	NOAA-06	35	-1.1421	0.0096	0.094	0.0009
NOAA-06	NOAA-07	120	0.1562	0.0076	-0.049	0.0004
NOAA-06	NOAA-09	63	0.4326	0.0068	0.068	0.0005
NOAA-07	NOAA-08	72	-0.3659	0.0064	0.042	0.0005
NOAA-07	NOAA-09	12	0.2534	0.0232	0.194	0.0045
NOAA-08	NOAA-09	11	0.6461	0.0174	0.310	0.0053
NOAA-09	NOAA-10	19	-0.6136	0.0182	0.616	0.0112
NOAA-10	NOAA-11	213	0.8771	0.0046	0.726	0.0033
NOAA-10	NOAA-12	18	0.2192	0.0119	0.094	0.0012
NOAA-11	NOAA-12	311	-0.7132	0.0031	0.662	0.0020
NOAA-11	NOAA-14	57	-0.6064	0.0081	0.385	0.0031
NOAA-12	NOAA-14	283	0.1328	0.0058	0.521	0.0030

Table 3. Target Temperature Factor Sensitivity Analysis

Satellite	Target Temperature Factor α	Std. Dev. of α	Sensitivity of Trend (dTrend/d α) (K/Decade)	Contribution to Std. Dev. of Trend (K/Decade)
TIROS-N	+0.0023	0.0071	-0.001	0.0000
NOAA-06	+0.0005	0.0014	1.689	0.0024
NOAA-07	+0.0166	0.0025	-0.045	0.0001
NOAA-08	+0.0300	0.0030	-0.105	0.0003
NOAA-09	+0.0195	0.0092	-0.789	0.0072
NOAA-10	+0.0032	0.0012	-0.329	0.0004
NOAA-11	+0.0277	0.0009	-2.756	0.0024
NOAA-12	+0.0059	0.0006	2.450	0.0015
NOAA-14	+0.0289	0.0030	-0.958	0.0029

Table 4. Offsets and nonlinear target multipliers derived from regression to the global average land and ocean pentad series for MSU channel 2, using the central 5 fields of view.

Satellite	Ocean-Only Offsets (K)	Land-Only Offsets (K)	Land and Ocean	Target Multipliers
TIROS-N	-1.3218	-1.3554	-1.3244	+0.0023
NOAA-06	-0.1798	-0.2392	-0.1915	+0.0005
NOAA-07	-0.3393	-0.3700	-0.3438	+0.0166
NOAA-08	0.0266	-0.0472	+0.0078	+0.0300
NOAA-09	-0.6117	-0.5515	-0.5922	+0.0195
NOAA-10	0.0000	0.0000	0.0000	+0.0032
NOAA-11	-0.8829	-0.8436	-0.8721	+0.0277
NOAA-12	-0.1672	-0.1301	-0.1553	+0.0059
NOAA-14	-0.2898	-0.1814	-0.2554	+0.0289

Table 5. Long-term trends in the MSU 2 brightness temperature anomalies for 1979 through 2001. The Prabhakara et al value is over the period from 1979-1999, our value for this time period is 0.095 K/Decade.

	Analysis Method	Trend (K/Decade)	RMS of Resid.(K)
Ocean-only	Diurnally corrected	0.098 +/- 0.028	0.033
	No diurnal correction	0.091 +/- 0.030	0.034
	Spencer and Christy, Vers. 5.0	-0.011	
Land-only	Diurnally corrected	0.087 +/- 0.046	0.064
	No diurnal correction	0.023 +/- 0.046	0.077
	Spencer and Christy, Vers. 5.0	0.050	
Global	Diurnally corrected	0.097 +/- 0.028	0.031
	No diurnal correction	0.067 +/- 0.028	0.040
	Spencer and Christy, Vers. 5.0	0.009	
	Prabhakara et al	0.13	

Table 6. Summary of important differences between the RSS and CS Methods.

	RSS	UAH
Diurnal Adjustment: Origin	Derived using hourly output from the CCM3 climate model, and a radiative transfer model.	Derived using observed cross-scan differences measured by the MSU instruments
Diurnal Adjustment: Methodology	Adjustments all made to a single reference time (noon, local time).	Adjustments made to different reference times for each satellite (local time of first observation for each month of instrument operation).
Determination of Target Factors	All valid 5 day averages with simultaneous observations for two or more satellites used in least-square regression procedure.	Only long-term periods of satellite overlap used. Some target factors set to zero if their improvement of intersatellite differences insufficient to warrant use.
Determination of Intersatellite Offsets	Determined is a unified way during the regression procedure for determining target factors.	Determined using a single path or “backbone” that links together the various satellites.
Smoothing Before Target Factor Determination	5-day averages	60 to 120-day averages

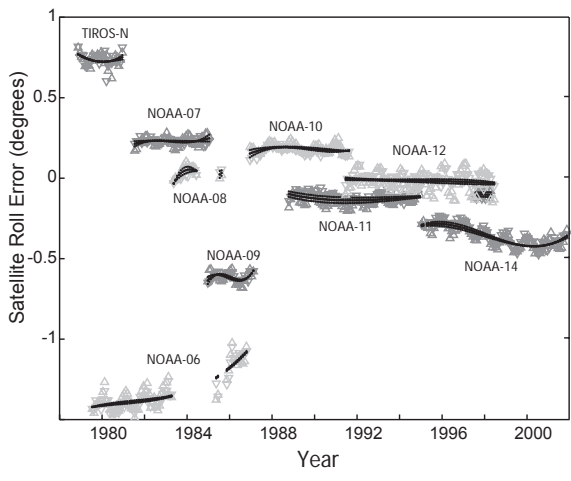


Figure 1.

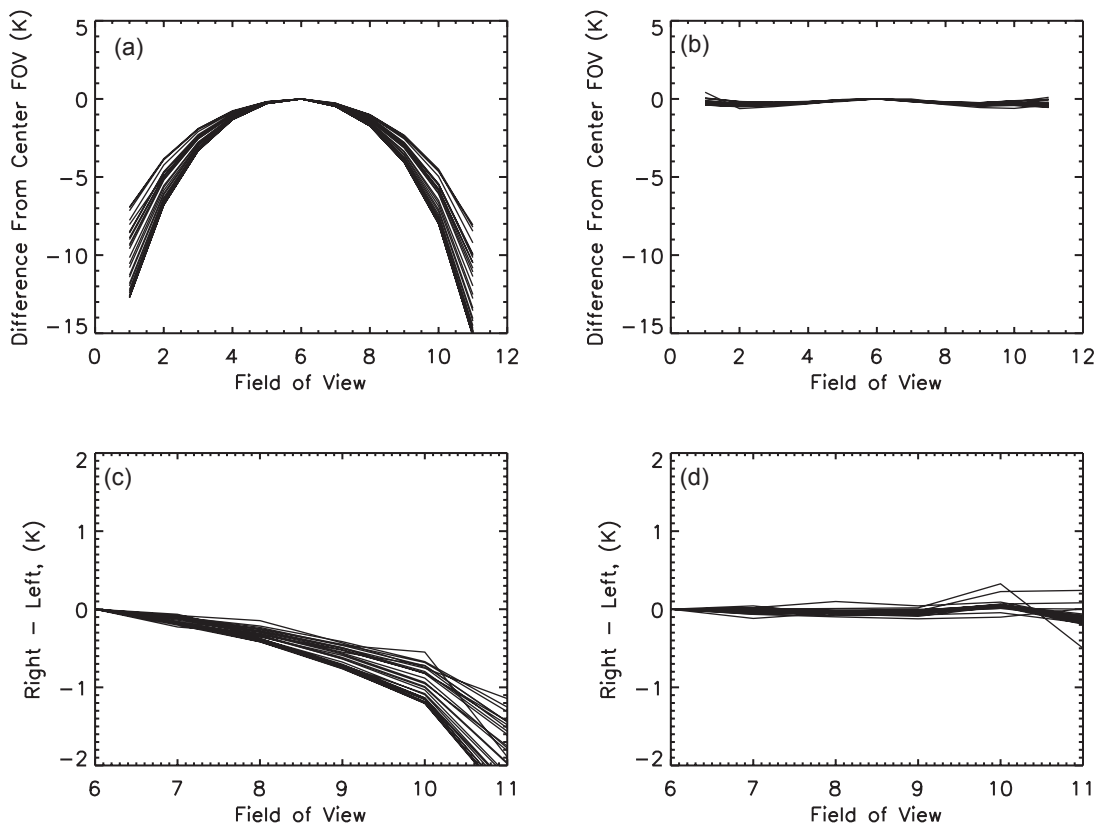


Figure 2.

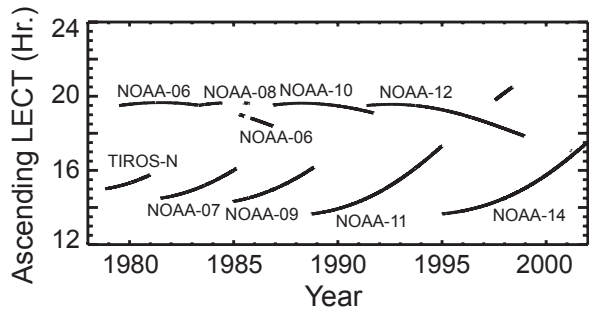


Figure 3.

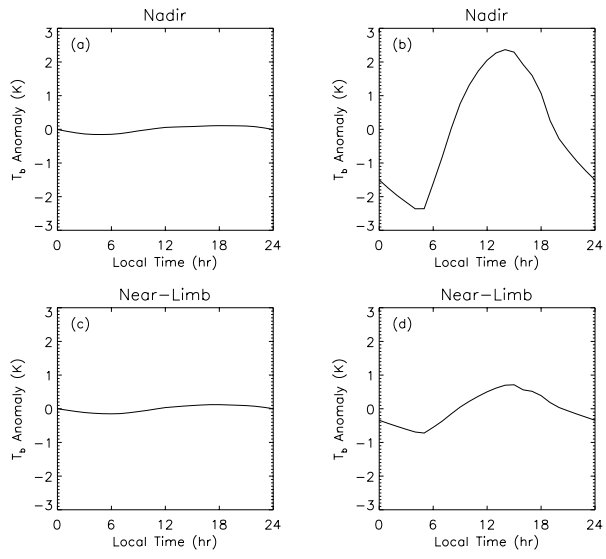


Figure 4.

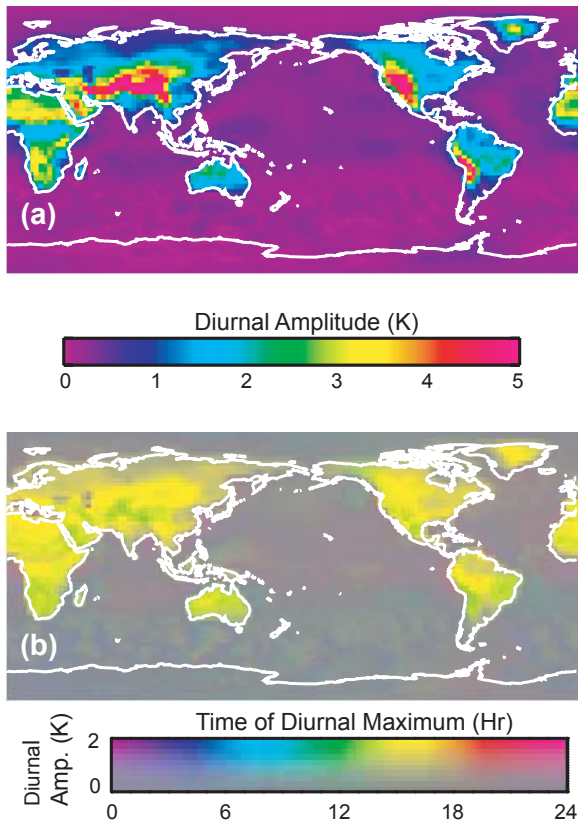


Figure 5.

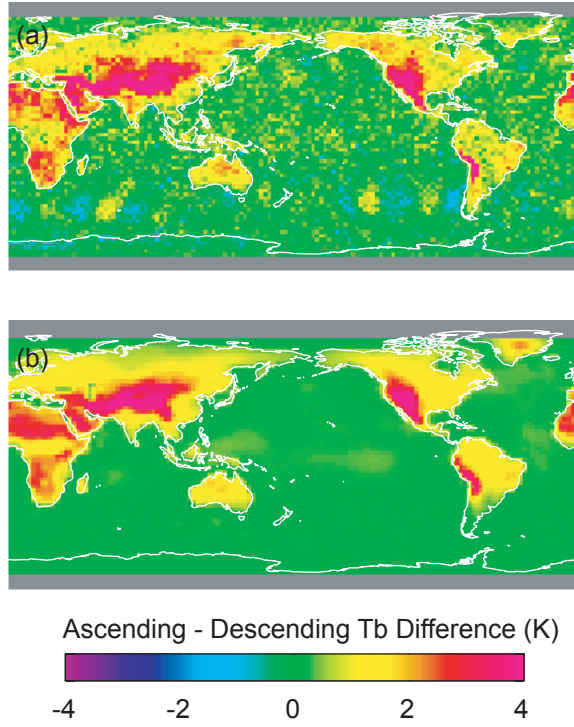


Figure 6.

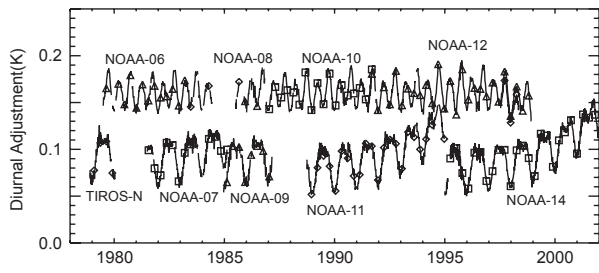


Figure 7.

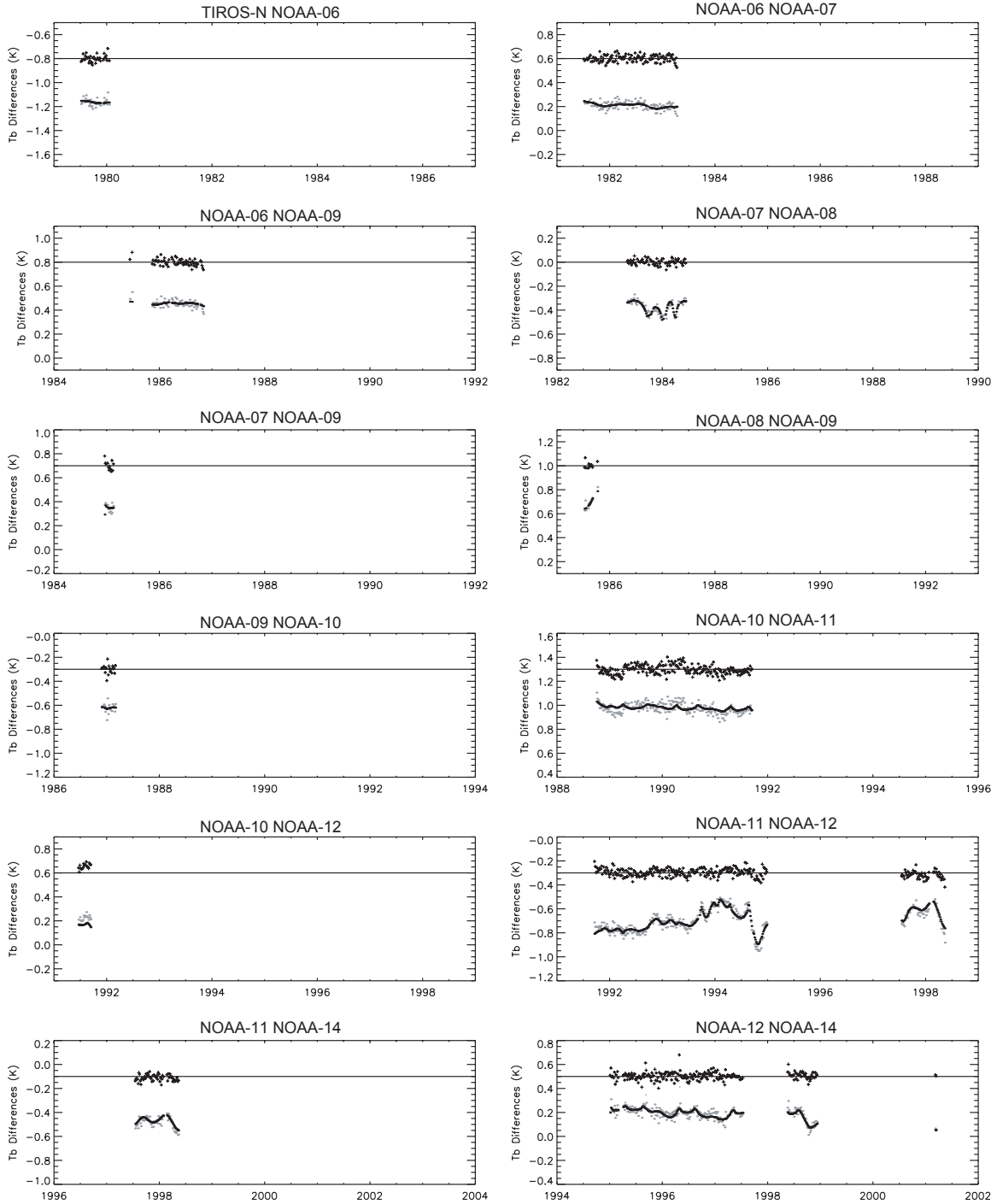


Figure 8.

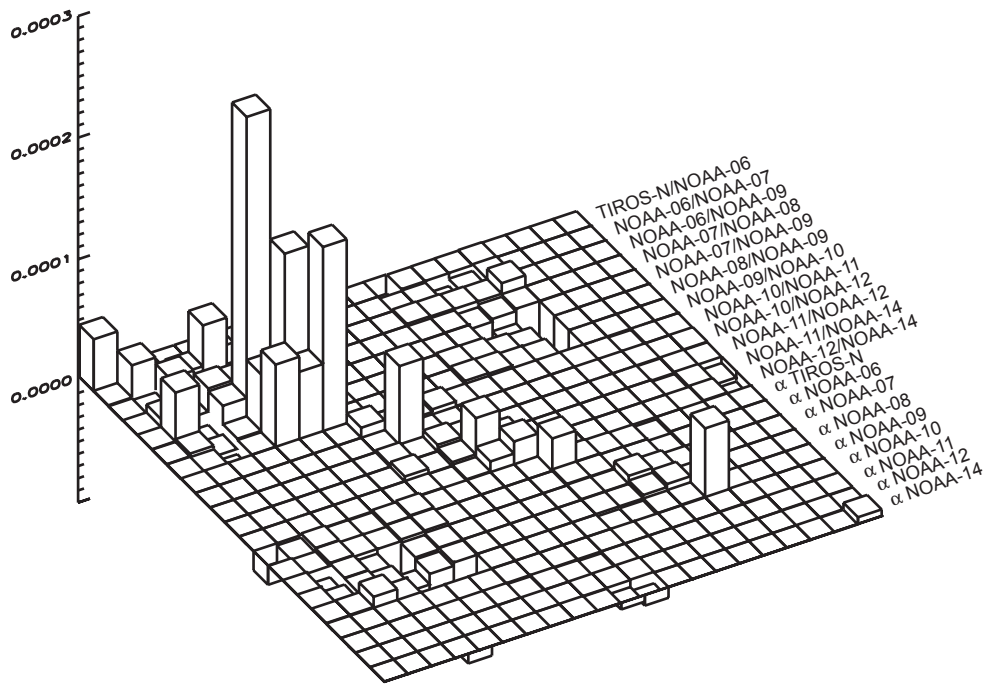


Figure 9.

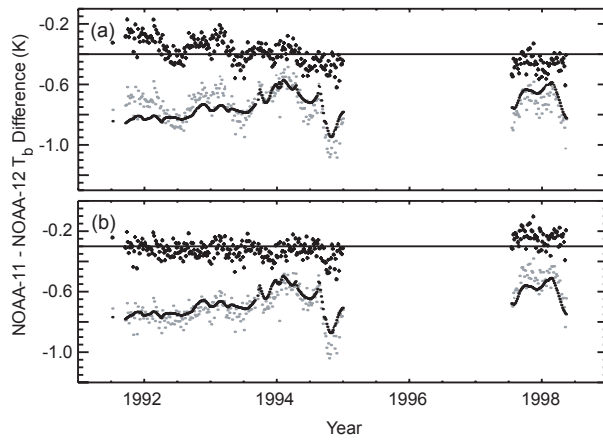


Figure 10.

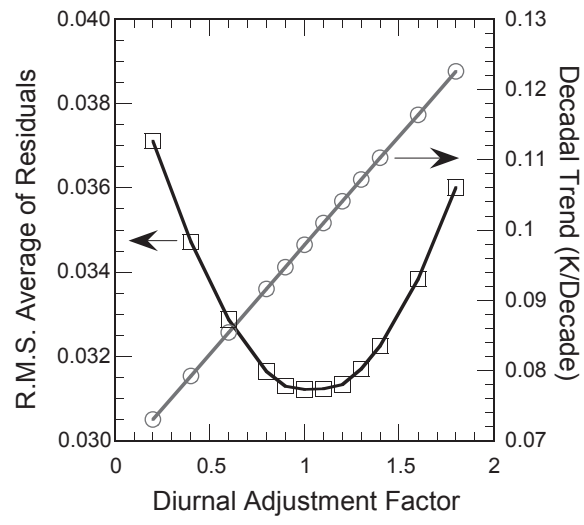


Figure 11.

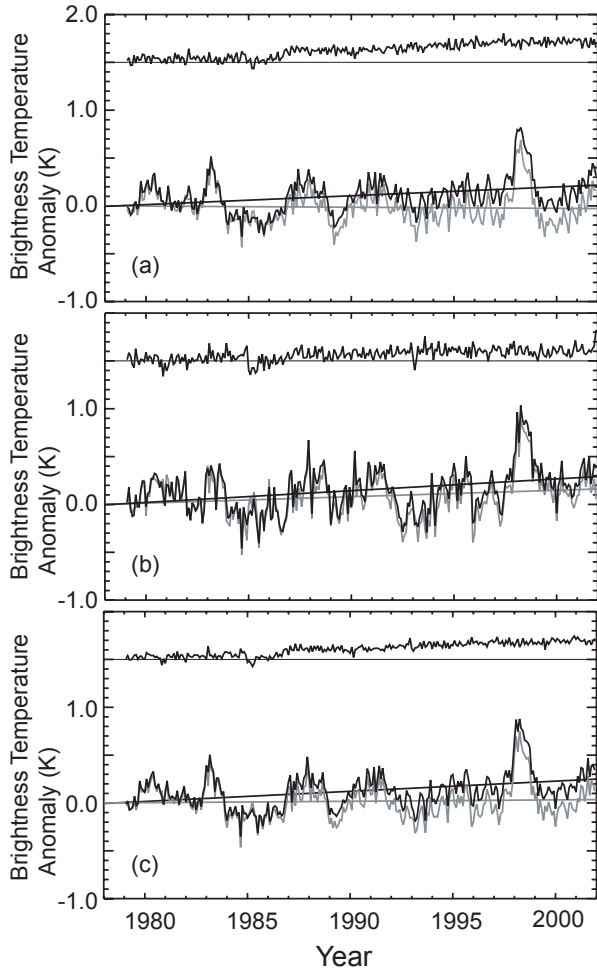


Figure 12.

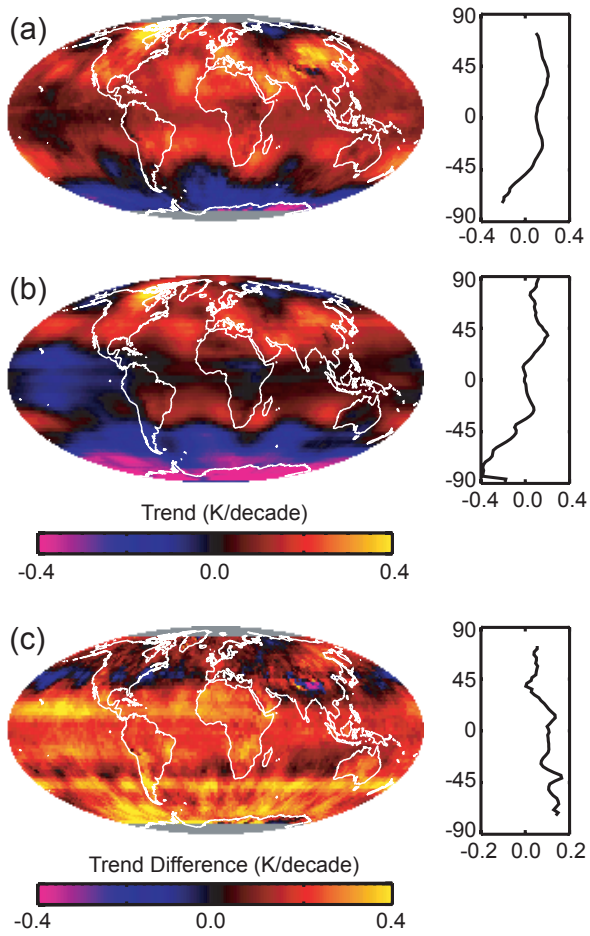


Figure 13.

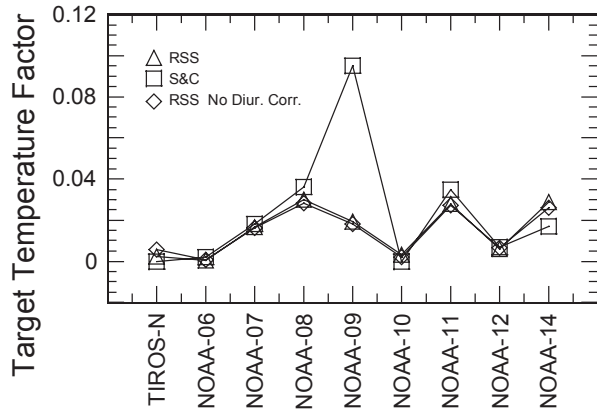


Figure 14.